

## THE TWO POWER LIMITS CONDITIONING STEP FREQUENCY IN HUMAN RUNNING

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### SUMMARY

1. At high running speeds, the step frequency becomes lower than the apparent natural frequency of the body's bouncing system. This is due to a relative increase of the vertical component of the muscular push and requires a greater power to maintain the motion of the centre of gravity,  $\dot{W}_{\text{ext}}$ . However, the reduction of the step frequency leads to a decrease of the power to accelerate the limbs relatively to the centre of gravity,  $\dot{W}_{\text{int}}$ , and, possibly, of the total power  $\dot{W}_{\text{tot}} = \dot{W}_{\text{ext}} + \dot{W}_{\text{int}}$ .

2. In this study we measured  $\dot{W}_{\text{ext}}$  using a force platform,  $\dot{W}_{\text{int}}$  by motion picture analysis, and calculated  $\dot{W}_{\text{tot}}$  during human running at six given speeds (from 5 to 21 km h<sup>-1</sup>) maintained with different step frequencies dictated by a metronome. The power was calculated by dividing the positive work done at each step by the duration of the step (step-average power) and by the duration of the positive work phase (push-average power).

3. Also in running, as in walking, a change of the step frequency at a given speed has opposite effects on  $\dot{W}_{\text{ext}}$ , which decreases with increasing step frequency, and  $\dot{W}_{\text{int}}$ , which increases with frequency; in addition, a step frequency exists at which  $\dot{W}_{\text{tot}}$  reaches a minimum. However, the frequency for a minimum of  $\dot{W}_{\text{tot}}$  decreases with speed in running, whereas it increases with speed in walking. This is true for both the step-average and the push-average powers.

4. The frequency minimizing the step-average power equals the freely chosen step frequency at about 13 km h<sup>-1</sup>: it is higher at lower speeds and lower at higher speeds. The frequency minimizing the push-average power approaches the freely chosen step frequency at high speeds (around 22 km h<sup>-1</sup> for our subjects).

5. It is concluded that the increase of the vertical push does reduce the step-average power, but that a limit is set by the increase of the push-average power. Between 13 and 22 km h<sup>-1</sup> the freely chosen step frequency is intermediate between a frequency minimizing the step-average power, eventually limited by the maximum oxygen intake (aerobic power), and a frequency minimizing the push-average power, set free by the muscle immediately during contraction (anaerobic power). The first need prevails at the lower speed, the second at the higher speed.

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## INTRODUCTION

The freely chosen step frequency in human walking is similar to a frequency at which the sum of the mechanical work done per minute to move the centre of gravity of the body relative to the surroundings ( $\dot{W}_{\text{ext}}$ ) and to move the limbs relative to the centre of gravity ( $\dot{W}_{\text{int}}$ ) is minimum (Cavagna & Franzetti, 1986).

Contrary to the pendular motion of walking, the gravitational potential energy changes and the kinetic energy changes of the centre of mass of the body are in phase during running: this is suggestive of an elastic rebound of the body as the energy is alternately absorbed and restored by the muscles. The lower limb flexes and its contracted muscles are forcibly stretched, performing negative work, during the deceleration downwards and forwards and it re-extends, i.e. the contracted muscles shorten, performing positive work, during the subsequent acceleration upwards and forwards. The 'bounce' of the body would therefore consist in this flexion and re-extension of the lower limb checked by the contracted muscles. As described in a previous study (Cavagna, Franzetti, Heglund & Willems, 1988), the step period and the vertical oscillation of the centre of gravity of the body can be divided into two parts: a part during which the vertical force exerted on the ground is greater than body weight (lower part of the oscillation, taking place during contact of the foot on the ground) and a part during which the vertical force is smaller than body weight (upper part of the oscillation, taking place during both ground contact and aerial phase). The duration of the lower part of the vertical oscillation (rather than the whole time of contact) has been considered to be one-half of the period of the apparent elastic bounce of the body. At low speeds of running of both humans and birds, the duration and the amplitude of the lower part of the vertical oscillation of the centre of gravity are about equal to those of the upper part (symmetric rebound). In this case, the step frequency equals the apparent natural frequency of the bouncing system. At very low running speeds of humans, the aerial phase tends to disappear and the total contact time approaches the period of the system as predicted by a spring-mass model hopping in place with a very low landing velocity (Blickhan, 1989). At high speeds of running, the duration and the amplitude of the upper part of the oscillation are greater than those of the lower part (asymmetric rebound), and the step frequency is lower than the frequency of the system. The asymmetry is due to a relative increase in the vertical push leading to an average vertical acceleration of the centre of gravity greater than  $1g$ : this, in turn, makes the amplitude and the duration of the upper part of the vertical oscillation (when the average vertical acceleration cannot exceed  $1g$ ) greater than those of the lower part. The asymmetric rebound increases the work per minute to maintain the motion of the centre of gravity, but involves a lower step frequency and consequently decreases the work per minute to accelerate the limbs. The hypothesis has been put forward that the asymmetric rebound is adopted to reduce, as in walking, the total mechanical power  $\dot{W}_{\text{tot}} = \dot{W}_{\text{ext}} + \dot{W}_{\text{int}}$  (Cavagna *et al.* 1988).

This hypothesis has been tested in this study by measuring  $\dot{W}_{\text{ext}}$  and  $\dot{W}_{\text{int}}$  in humans running at a given speed with different step frequencies. The results show that in order to assess how the mechanical power output affects the freely chosen step frequency, it is necessary to make a distinction between power averaged over the

whole step, as previously measured (Cavagna & Franzetti, 1986; Kaneko, Matsumoto, Ito & Fuchimoto, 1987) and average power during the push. The first turns out to be particularly important at intermediate running speeds, the second at high running speeds.

Some of these results have been reported briefly (Cavagna, Willems, Franzetti & Detrembleur, 1989).

#### METHODS

*Subjects and experimental procedure.* Experiments were performed on five untrained male subjects (see Table 1). Informed consent of the subjects was obtained. The subjects wore gym shoes and ran at six given speeds (5.3, 8, 11, 14, 17 and 21 km h<sup>-1</sup>), following a mark pulled by a motor. Each speed was maintained with a freely chosen step frequency and with different step frequencies dictated by a metronome. In this study, as in the others from the same laboratory, the word 'step' means 'half a stride', not the distance travelled while one foot is on the ground as sometimes used (e.g. Kram & Taylor, 1990). A run was used for calculations only when the running speed, measured by means of two photocells, was within 6% of the indicated one. Some subjects (N.H., W.P. and T.J.) ran also at other speeds, between 5 and 22 km h<sup>-1</sup>, with a freely chosen step frequency (these data were used for Figs 2 and 5).

*Measurement of the external work.* The mechanical work done during each step in lifting and accelerating the centre of gravity of the body in the forward and vertical directions,  $W_{\text{ext}}$ , was measured (347 runs) by means of a platform (4 m long and 0.5 m wide), sensitive to the vertical and forward components of the force exerted by the foot against the ground. The characteristics of this platform, the principle of the method and the procedure followed to compute velocity, displacement and mechanical energy changes of the centre of mass of the body by integration of the force-time platform's records are described in detail by Cavagna (1975) and by Cavagna, Franzetti & Fuchimoto (1983). The mechanical energy changes of the centre of mass of the body are illustrated in the upper part of Fig. 1 (top three lines: the second and third tracings from the left are plotted exactly as obtained during the experiment, i.e. from two maxima of the upward velocity, whereas the first tracing, obtained from two maxima of the downward velocity, was redrawn, for clarity, as the other two). In each set of tracings, the upper curve indicates the changes in kinetic energy of forward motion,  $E_{k,f} = MV_f^2/2$  where  $M$  is the body's mass and  $V_f$  the instantaneous forward velocity of the centre of gravity; the dashed line in the middle tracing indicates the change in gravitational potential energy,  $E_p$ , due to the vertical displacement of the centre of gravity; the continuous line in the middle tracing indicates the sum of the potential energy and of the kinetic energy of vertical motion ( $E_p + E_{k,v}$  where  $E_{k,v} = MV_v^2/2$ ,  $V_v$  being the instantaneous velocity of the centre of gravity in the vertical direction) the lower curve gives the total mechanical energy  $E_{\text{tot}} = E_{k,f} + E_p + E_{k,v}$ . The positive work done at each step to move the centre of gravity,  $W_{\text{ext}}$ , equals the increment of the curve  $E_{\text{tot}}$  (this procedure neglects the small amount of work done against air resistance and to sustain the lateral displacement of the centre of gravity). Increasing the step frequency, particularly at low running speeds, may lead to a modification of the mechanics of running towards that of walking: this was checked by measuring the amount of transfer between potential and kinetic energy, given by

$$\text{Percentage of recovery} = ((W_f + W_v - W_{\text{ext}})/(W_f + W_v)) 100, \quad (1)$$

where  $W_v$  is the work done against gravity and  $W_f$  is the work done to accelerate forward the centre of gravity of the body. Since the percentage of recovery is high in walking and almost nil in running (Cavagna, Thys & Zamboni, 1976), the data of  $W_{\text{ext}}$  were used only if the percentage of recovery was less than 11%.

*Measurement of the internal work.* The mechanical work done to accelerate the limbs relatively to the centre of gravity of the body,  $W_{\text{int}}$ , was measured, as described by Fenn (1930) and by Cavagna & Kaneko (1977), from the angle made by the arm, forearm, thigh and lower leg with the horizontal during a stride (two steps). These angles were measured by means of a Selspot II system (except for the runs at 5.3 and 8 km h<sup>-1</sup> of subject F.P., which were analysed by means of a stroboscopic system flashing at 25 Hz). Two infra-red cameras were placed 6.3 m apart and 6.3 m from the

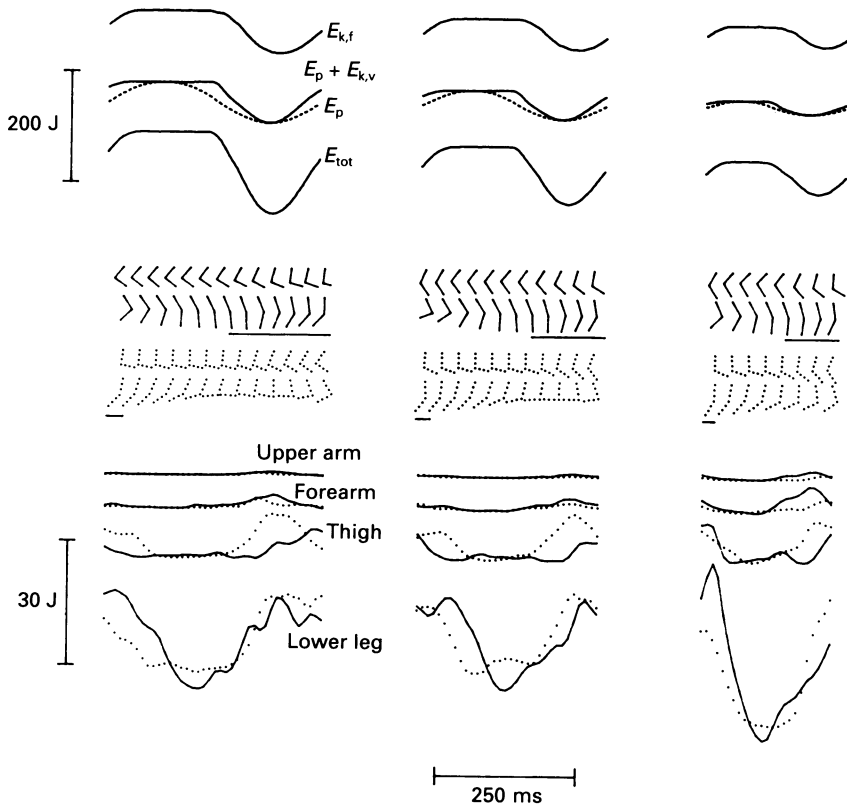


Fig. 1. Computer plots of the mechanical energy changes of the centre of mass of the body (top three lines) and of the kinetic energy changes of the limbs due to the velocity relative to the centre of gravity (bottom four lines) during running at about  $13.9 \text{ km h}^{-1}$  with three different frequencies: 2.6 Hz (left column), 3.1 Hz (middle column) and 4.1 Hz (right column) (subject C.G.). See Methods for description of the top tracings. The middle and the lower sets of tracings illustrate the position and the kinetic energy of the limbs determined by motion picture analysis of a complete stride (two steps). The continuous lines refer to the first half of the stride and the dotted lines to the second half. The time interval between the dots of the bottom tracings is 10 ms. The 'stick man' (middle tracings), giving the angulation of the limbs, is plotted every 30 ms. Whereas the time correspondence between 'stick man' and lower tracings is exact, their time correspondence with the mechanical energy changes of the centre of mass (top tracings) and the time of contact with the ground (horizontal bars below the stick man) is approximated.

running line. The combined field of the cameras encompassed about 4 m of the track. Infra-red emitters were attached over the articulations of the shoulder, elbow, wrist, hip, knee and ankle. The system measured the co-ordinates of the spots in the forward, lateral and vertical directions with a sampling frequency of 100 Hz. The angles made by the limbs with the horizontal were computed using the co-ordinates in the forward and vertical directions only, neglecting the medio-lateral co-ordinates; as shown by Williams (1985) this procedure (2-D(1) in Williams's paper) does not involve an appreciable error when only one-side measurements are made without attempting to generate, from these, the simultaneous movements of the contralateral limbs (as in procedure 2-D(2)). Other imprecisions of the method have been discussed by Fenn (1930) and Cavagna & Kaneko (1977). The stride duration was determined by the time necessary for the limbs to return to their initial angulation. In order to reduce noise, the curves of the angular displacement as a function of time

were smoothed by a least-squares method (Savitzky & Golay, 1964) over 70–130 ms time intervals (depending on the step frequency and the running speed). The angular velocity was computed from the average slope of this curve over time intervals of 20 ms. The kinetic energy of the limb relative to the trunk was calculated as the sum of its translational and rotational energies (Cavagna & Kaneko, 1977). The internal work during each stride was computed assuming a complete transfer of kinetic energy between the two segments of each limb: this minimum value has been used to compensate for a possible error made by assuming no transfer between internal and external work in the calculation of the total work (for a discussion of this point see Cavagna & Kaneko, 1977).

TABLE 1. Characteristics of the subjects

Subject	Age (years)	Weight (kg)	Height (m)	Length (m)				No. of runs	
				Upper arm	Forearm	Thigh	Lower leg	$\dot{W}_{\text{ext}}$	$\dot{W}_{\text{int}}$
C. G.	54	76.9	1.77	0.31	0.235	0.417	0.416	64	42
F. P.	31	71.5	1.76	0.27	0.235	0.395	0.395	81	48
W. P.	32	79.8	1.78	0.3	0.265	0.46	0.365	76	48
T. J.	34	76.5	1.85	0.287	0.278	0.464	0.436	62	50
N. H.	35	69.9	1.77	0.3	0.26	0.42	0.41	64	41
Mean	37	74.9	1.79	0.294	0.255	0.431	0.404		

The internal work done during one step was calculated assuming that the energy spent to accelerate the limbs of one side of the body during one stride was equal to the energy spent to accelerate the limbs of both sides of the body during one step (Fig. 1). As for the external work, measurements were made at 5.3, 8, 11, 14 and 17 km h<sup>-1</sup> (229 runs). Measurements at 21 km h<sup>-1</sup> could not be made because the distance covered during one stride was greater than the field of the cameras.

*Calculation of the normalized internal work.* The internal work was also calculated, at all step frequencies and speeds, from the relationship obtained between a dimensionless, normalized value of  $\dot{W}_{\text{int}}$  and step length,  $L$ , during running with a freely chosen step frequency. The normalization was made by dividing the mass specific internal work per step by the square of the running speed. The meaning of this procedure can be understood considering that the kinetic energy of the lower limb, which corresponds to 80–90% of the internal work (Cavagna & Kaneko, 1977), can be written, assuming for simplicity the lower limb equivalent to a single segment only, as

$$E_k = m \omega^2 (\kappa^2 + \sigma^2) / 2, \quad (2)$$

where  $m$  is the mass of the equivalent segment,  $\omega$  its angular velocity,  $\kappa$  the radius of gyration around its centre of gravity and  $\sigma$  the distance from the segment's centre of gravity to the hip joint. During the time of contact,  $t_c$ ,

$$\omega \approx (L_c/l)/t_c \approx V_t/l, \quad (3)$$

where  $L_c$  is the forward displacement during contact, and  $l$  is the length of the lower limb. Substituting in eqn (2) and dividing by the square of the speed of running and the body's mass, a dimensionless value is obtained

$$E_k/(M V_t^2) = m/(2M) (\kappa^2 + \sigma^2)/l^2, \quad (4)$$

showing that the normalized work will depend on the distribution of the mass of the equivalent segment relatively to the centre of gravity of the body: in turn this distribution depends on the degree of flexion and the morphology of the lower limb. A decrease of  $(\kappa^2 + \sigma^2)$  at high speeds, due to a greater flexion of the leg over the thigh, may explain, at least in part, the decrease of the normalized internal work with increasing step length (Fig. 2). The curve in Fig. 2, calculated by the least-squares method from data obtained during running with a freely chosen step frequency, obeys the empirical equation

$$\dot{W}_{\text{int, norm}} = 0.1451 \times 10^{-0.2091 L}, \quad (5)$$

where  $L$  is given in metres ( $r = 0.773$ ,  $n = 96$ ). The internal power calculated from eqn (5) is in good agreement with the experimental results obtained during running at frequencies dictated by the metronome (Figs 3 and 4). This indicates that the movement of the limbs at a given step length is not drastically affected by the artificial change of the step frequency. For this reason eqn (5) was used to calculate the total work also at  $21 \text{ km h}^{-1}$ , i.e. at a speed where no experimental data of internal work could be obtained.

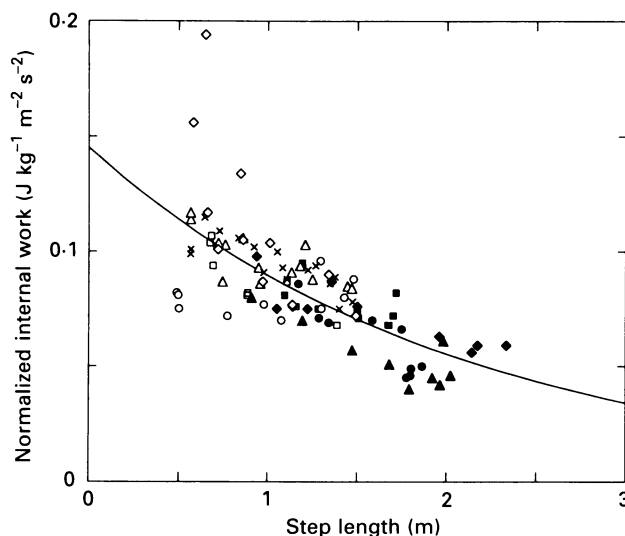


Fig. 2. The normalized internal work, i.e. the positive internal work done at each step divided by the mass of the body and the square of the velocity of running, is given as a function of the step length during running with a freely chosen step frequency. The filled symbols refer to the data of Cavagna & Kaneko (1977) and the open symbols to those of the present study. The symbols refer to different subjects as follows: ■ and □, C.G.; ●, Z.A.; ▲, S.M.; ◆, C.P.; ○, F.P.; △, W.P.; ×, T.J.; ◇, N.H. The continuous line was fitted through the points by the least-squares method (eqn (5) in the text).

*Calculation of the average power during the step and during the push.* The positive work done at each step (both external and internal) was divided by the step period to calculate the average power output over the whole step ( $\dot{W}_{\text{ext, step}}$  and  $\dot{W}_{\text{int, step}}$  in Fig. 3) and by the duration of the positive work phase to calculate the average power during the push ( $\dot{W}_{\text{ext, push}}$  and  $\dot{W}_{\text{int, push}}$  in Fig. 4). The duration of the external positive work phase was measured by the total time of increment of the  $E_{\text{tot}}$  curve (Fig. 1). The duration of the positive work done in accelerating the limbs was taken as the average between the total duration of the increases of kinetic energy of the upper limb (upper arm plus forearm) and of the lower limb (thigh plus lower leg). In running the ratio  $\dot{W}_{\text{int, push}}/\dot{W}_{\text{int, step}}$  is  $2.00 \pm 0.15$  (mean  $\pm$  s.d.,  $n = 229$ ) at all speeds whereas the ratio  $\dot{W}_{\text{ext, push}}/\dot{W}_{\text{ext, step}}$  increases with the running speed from about 2 at  $5 \text{ km h}^{-1}$  to 3.5 at  $21 \text{ km h}^{-1}$ . The  $\dot{W}_{\text{ext}}$  curves in Figs 3 and 4 obey the empirical equation

$$\dot{W}_{\text{ext}} (\text{W kg}^{-1}) = a f^{-b} (\text{Hz}). \quad (6)$$

The values of the constants  $a$  and  $b$  were calculated by the least-squares method and are given, for each speed, in Table 2. The internal power curves in Fig. 3 were determined by multiplying  $\dot{W}_{\text{int, norm}}$  per step (calculated from eqn (5)) by the step frequency and the square of the running speed; those in Fig. 4 were determined by doubling the values on the ordinates of the curves in Fig. 3. The total mechanical power  $\dot{W}_{\text{tot}}$  was determined by summing the curves  $\dot{W}_{\text{ext}}$  and  $\dot{W}_{\text{int}}$ : as mentioned above this procedure assumes no energy transfer between  $\dot{W}_{\text{ext}}$  and  $\dot{W}_{\text{int}}$ .

TABLE 2. Average data from the experiments

Constants of eqn (6):  $\dot{W}_{\text{ext}} (\text{W kg}^{-1}) = af^{-b} (\text{Hz})$ 

Running speeds (km h <sup>-1</sup> )		$\dot{W}_{\text{ext, step}}$			$\dot{W}_{\text{ext, push}}$		
$\dot{W}_{\text{int}}$	$\dot{W}_{\text{ext}}$	<i>a</i>	<i>b</i>	<i>r</i>	<i>a</i>	<i>b</i>	<i>r</i>
5.32 ± 0.14 (61)	5.26 ± 0.15 (52)	6.942	1.238	0.89	15.512	1.292	0.8
7.96 ± 0.19 (58)	7.99 ± 0.22 (59)	9.992	1.27	0.94	30.829	1.503	0.92
11.05 ± 0.33 (48)	11.04 ± 0.32 (57)	12.196	1.15	0.94	49.609	1.503	0.89
14.12 ± 0.36 (39)	14.06 ± 0.32 (65)	12.549	0.94	0.92	60.705	1.322	0.89
17.08 ± 0.45 (23)	16.91 ± 0.4 (56)	12.344	0.767	0.85	65.585	1.157	0.88
	20.97 ± 0.48 (58)	15.076	0.717	0.72	98.099	1.197	0.75

Running speed values expressed as means ± S.D. followed by the number, *n*, in parentheses. *a* and *b*, constants from eqn (6). *r*, correlation coefficient.

## RESULTS

The mechanical power output required to increase the kinetic and gravitational potential energy of the centre of mass of the body,  $\dot{W}_{\text{ext}}$ , and that required to accelerate the limbs relatively to the centre of gravity,  $\dot{W}_{\text{int}}$ , together with their sum,  $\dot{W}_{\text{tot}} = \dot{W}_{\text{ext}} + \dot{W}_{\text{int}}$ , are given as a function of the step frequency for six different speeds of running in Figs 3 and 4. The filled arrows on the abscissa indicate the freely chosen step frequency at each speed. Figure 3 refers to the step-average power and Fig. 4 to the push-average power.

It can be seen that in running, as in walking, a change of the step frequency at a given speed has opposite effects on  $\dot{W}_{\text{ext}}$ , which decreases with increasing step frequency, and  $\dot{W}_{\text{int}}$ , which increases with step frequency. In addition, the total mechanical power  $\dot{W}_{\text{tot}}$  reaches a minimum at a step frequency indicated on the abscissa by the open arrow. At intermediate speeds, this minimum is within the range of the experimental data, whereas at the lowest and the highest speeds it usually lies beyond this range, indicating that it was impossible for our subjects to attain the frequency minimizing the total mechanical power.

The step frequency at which the total power is at a minimum is plotted as a function of the speed in Fig. 5 for comparison with the freely chosen step frequency, *f*; analogous data obtained in walking (Cavagna & Franzetti, 1986) are also illustrated in Fig. 5. In running, contrary to walking, the step frequency minimizing the total power decreases with speed. In addition, the freely chosen step frequency and the optimal step frequency (*f*<sub>o</sub>) change similarly with speed in walking, whereas they change in an opposite way in running.

When the running speed increases from 5.3 to 21 km h<sup>-1</sup>, the frequency minimizing the step-average power, *f*<sub>o, step</sub>, becomes progressively smaller than the frequency minimizing the push-average power, *f*<sub>o, push</sub>. This is due to the fact that the ratio  $\dot{W}_{\text{int, push}}/\dot{W}_{\text{int, step}} = 2$  at all speeds, whereas the ratio  $\dot{W}_{\text{ext, push}}/\dot{W}_{\text{ext, step}}$  increases with speed from 2 at 5.3 km h<sup>-1</sup> to 3.5 at 21 km h<sup>-1</sup>. A comparison of Figs 3 and 4 shows that the relative increase of  $\dot{W}_{\text{ext}}$  tends to shift the minimum of  $\dot{W}_{\text{tot}}$  towards high frequency values (open arrows in Fig. 4).

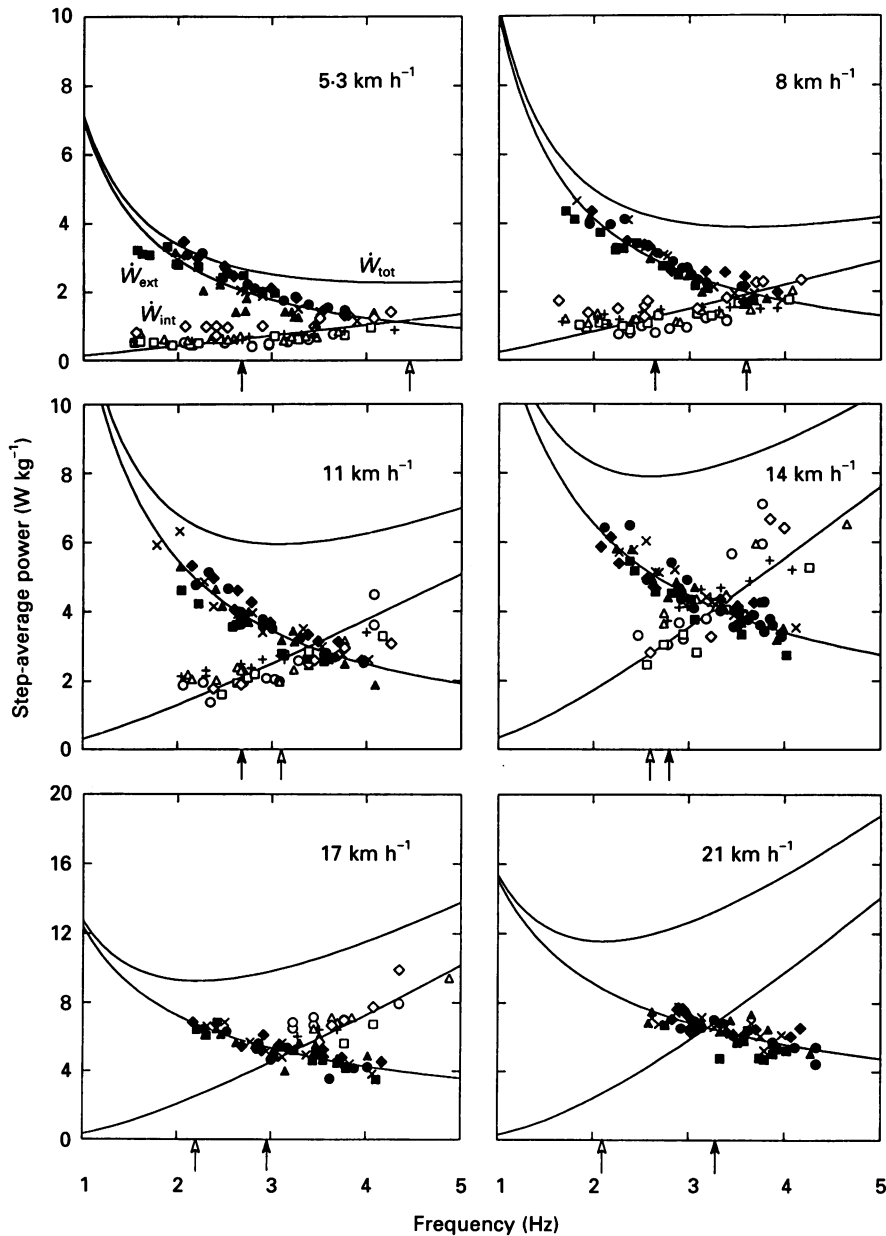


Fig. 3. The weight-specific mechanical power output during running, calculated by dividing the positive work done at each step by the duration of the step (step-average power), is given as a function of the step frequency at the six indicated speeds. Each point refers to a run made by a subject. The filled symbols and the  $\times$  indicate the power output to accelerate and lift the centre of gravity of the body,  $\dot{W}_{ext,step}$ ; the curves obey eqn (6) of the text. The open symbols and the  $+$  indicate the power to accelerate the limbs relative to the centre of gravity of the body  $\dot{W}_{int,step}$ ; the curves were calculated from normalized values of  $\dot{W}_{int}$  (eqn (5)) using the step lengths corresponding to the different frequencies indicated on the abscissa. No  $\dot{W}_{int}$  data could be obtained at 21 km h<sup>-1</sup> because stride length exceeded the camera's field. The upper curves  $\dot{W}_{tot}$  are the sum of the curves  $\dot{W}_{ext}$  and  $\dot{W}_{int}$ . A minimum of  $\dot{W}_{tot}$  is attained at the frequency indicated on the abscissa by



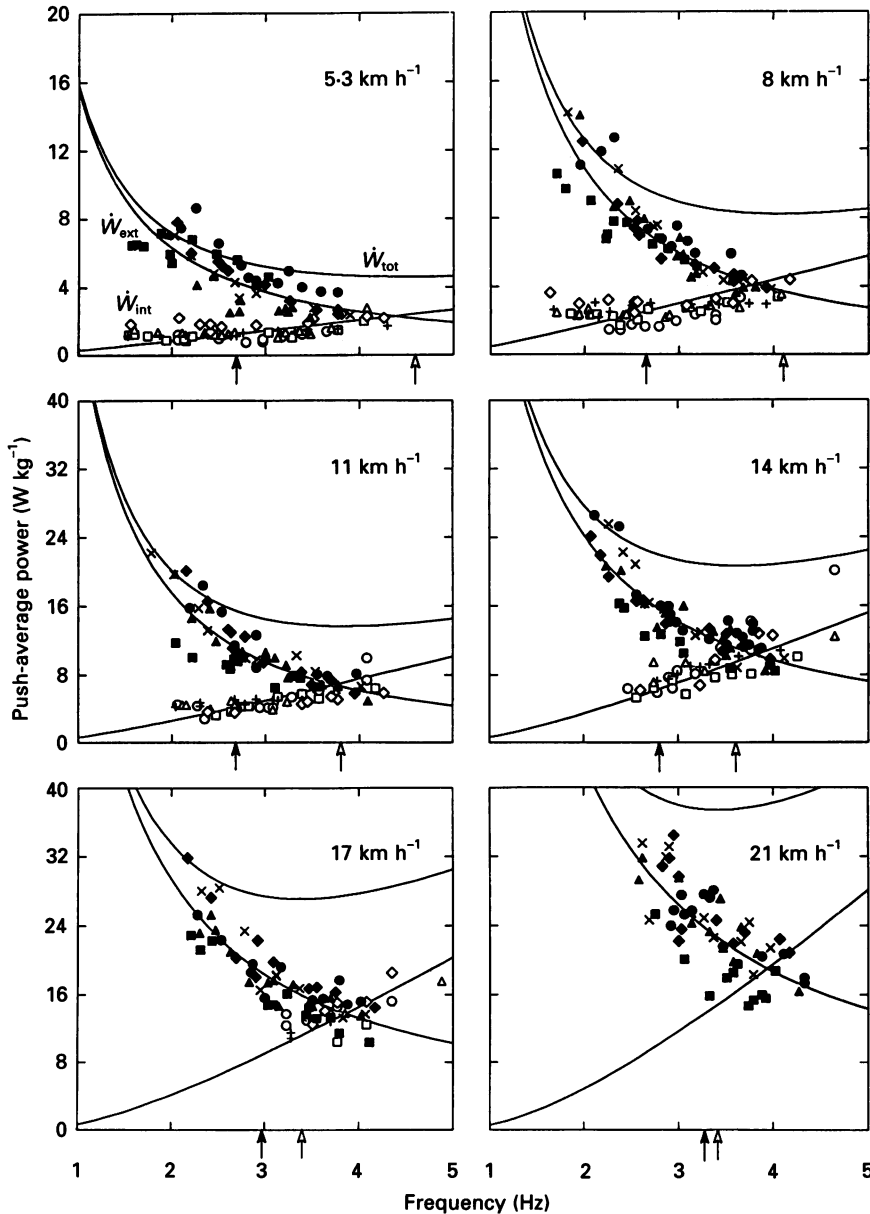


Fig. 4. The weight-specific mechanical power output during running, calculated by dividing the positive work done at each step by the duration of the positive work phase (push-average power), is given as a function of the step frequency. The values on the ordinate of the  $\dot{W}_{int, push}$  curves are exactly twice those of Fig. 3 whereas the values of  $\dot{W}_{ext, push}$ , also about twofold at 5.3 km h<sup>-1</sup>, increase with speed to values 3–4 times greater than those of Fig. 3. This leads to a shift of the minimum of  $\dot{W}_{tot, push}$  towards higher frequency values (open arrows). Symbols as in Fig. 3.

the open arrow; the filled arrow gives the freely chosen step frequency. The symbols refer to the different subjects as follows:  $\square$  and  $\blacksquare$ , C.G.;  $\circ$  and  $\bullet$ , F.P.;  $\triangle$  and  $\blacktriangle$ , W.P.;  $+$  and  $\times$ , T.J.;  $\diamond$  and  $\blacklozenge$ , N.H.

The frequency for a minimum of the step-average power,  $f_{o, \text{step}}$ , equals the freely chosen step frequency at about 13 km h<sup>-1</sup>: at higher and lower running speeds, a clear dissociation exists between  $f$  and  $f_{o, \text{step}}$ . On the contrary, the frequency for a minimum of the push-average power,  $f_{o, \text{push}}$ , approaches the freely chosen frequency

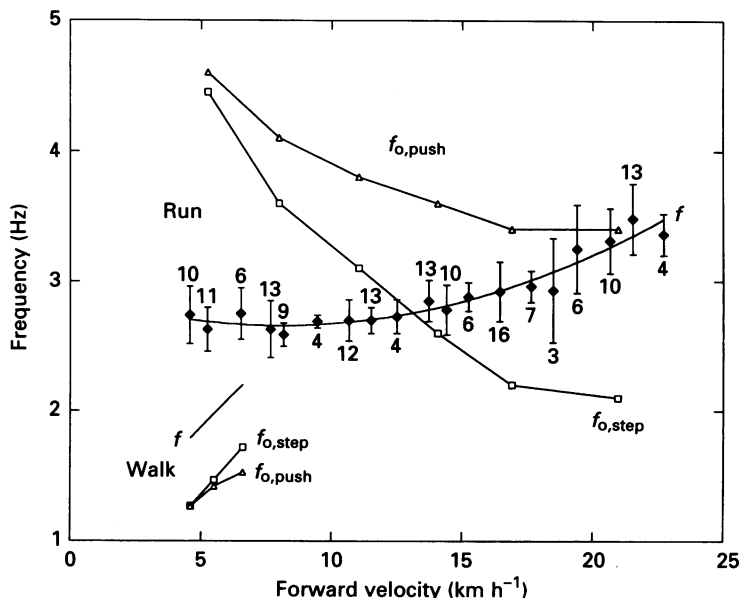


Fig. 5. The step frequency freely chosen during running,  $f$ , is given by the  $\blacklozenge$  as a function of the average speed of locomotion. The data points represent the average of 170 runs made by the five subjects of the present study and by four of them (all except N.H.) during a previous study (Cavagna *et al.* 1988); the vertical bars indicate the standard deviation and the figures near the symbols give the number of items in the mean; the equation of the curve

$$f = 2.905 - 0.6106 V_f + 0.003798 V_f^2 \quad (r = 0.965),$$

was used to calculate the frequencies indicated by the filled arrows in Figs 3 and 4; in the equation,  $f$  is given in Hz and  $V_f$  in km h<sup>-1</sup>. The continuous line without symbols on the bottom left corner of the figure refers to the freely chosen step frequency in walking (Cavagna & Franzetti, 1986). For both running and walking, the  $\square$  and  $\triangle$  indicate, respectively, the frequencies at which the step-average power ( $f_{o, \text{step}}$ : open arrows in Fig. 3) and the push-average power ( $f_{o, \text{push}}$ : open arrows in Fig. 4) are minimal.

at high speeds: about 22 km h<sup>-1</sup> for our subjects. Between 13 and 22 km h<sup>-1</sup>, the freely chosen step frequency is intermediate between  $f_{o, \text{step}}$  and  $f_{o, \text{push}}$ .

In walking, from about 4.3 to 6.7 km h<sup>-1</sup>,  $\dot{W}_{\text{int, push}}/\dot{W}_{\text{int, step}} = 1.9 \pm 0.11$  (mean  $\pm$  s.d.,  $n = 7$ ; calculated from Cavagna & Kaneko (1977) during free walking) and  $\dot{W}_{\text{ext, push}}/\dot{W}_{\text{ext, step}} = 2.04 \pm 0.21$  (mean  $\pm$  s.d.,  $n = 131$ ; calculated from Cavagna & Franzetti (1986) during free walking and during walking at an imposed frequency). These few data suggest that in walking  $f_{o, \text{step}}$  and  $f_{o, \text{push}}$  differ less than in running.

#### DISCUSSION

##### *Frequency for a minimum of power and freely chosen step frequency in running*

As explained in the Introduction, the aim of this study was to assess whether the asymmetric rebound, observed at high running speeds, could be explained as an attempt to reduce the step-average power (the only one previously measured). Figure

5 shows that at high running speeds, the frequency minimizing the step-average power,  $f_{o, \text{step}}$ , is lower than the freely chosen step frequency  $f$ . This indicates that the asymmetric rebound, which reduces the step frequency, does indeed reduce the step-average power. However, the freely chosen step frequency does not attain the frequency minimizing the step-average power. The discrepancy becomes progressively greater as the velocity of running increases. At 21 km h<sup>-1</sup> it was impossible for our subjects to run with the frequency, 2.1 Hz, which minimizes the step-average power. The finding that the frequency minimizing the push-average power approaches the freely chosen step frequency at high running speeds strongly suggests that at these speeds the step frequency is primarily conditioned by muscular performance.

The frequency at which the step-average power is at a minimum equals the freely chosen step frequency only at about 13 km h<sup>-1</sup>. The conclusion that the freely chosen step frequency in running is near to a frequency minimizing the step-average power (Kaneko *et al.* 1987) is therefore tenable only for a narrow range of speeds around 13 km h<sup>-1</sup>. At these speeds  $f < f_{o, \text{push}}$ , suggesting that the need to reduce the muscular power during the push does not affect the freely chosen step frequency. These intermediate speeds were similar to the speeds voluntarily chosen by our subjects during long distance exercise running.

In conclusion: in the range of speeds between 13 and 22 km h<sup>-1</sup> the freely chosen step frequency is intermediate between  $f_{o, \text{step}}$ , which minimizes a power which is eventually limited by the maximum oxygen intake (aerobic power) and  $f_{o, \text{push}}$ , which minimizes a power set free immediately by the muscle during contraction (anaerobic power). The first need prevails at the lower speed, the second at the higher speed.

Below 13 km h<sup>-1</sup>, the frequencies for a minimum of both the step-average and the push-average powers increase above the freely chosen step frequency. The work done at each step is greater than the possible minimum value, due to a greater work done against gravity. The vertical displacement of the centre of gravity of the body is about 3 cm during running at 5.3 km h<sup>-1</sup> with the maximum step frequency attained in the force-plate experiments (3.8 Hz), and about 6 cm during running at the same speed with the freely chosen step frequency (2.7 Hz). As a consequence of this persistence of the work done against gravity, the mechanical power during free running does not tend to zero when the speed reduces to zero, but to a positive intercept. On the contrary the predicted minimal mechanical power approaches zero when the velocity of running becomes zero. What is the reason for the additional work done against gravity during running at low speeds?

At low speeds, the whole-body vertical stiffness (Cavagna *et al.* 1988) increases when the step frequency is artificially increased towards  $f_o$ . An increase of the stiffness is accompanied by a tendency to shift from the compliant mechanism of running towards the rigid mechanics of walking. The shift towards the mechanism of walking, revealed as explained in the Methods by an increase of the percentage of recovery above 11 %, represented the limit in our experiments for the attainment of  $f_o$  at low running speeds.

*Why does the frequency for a minimum of mechanical power decrease with speed in running and increase with speed in walking?*

The opposite change of  $f_0$  with walking and running speed (Fig. 5) is a consequence of the difference between the pendular mechanism of walking and the bouncing

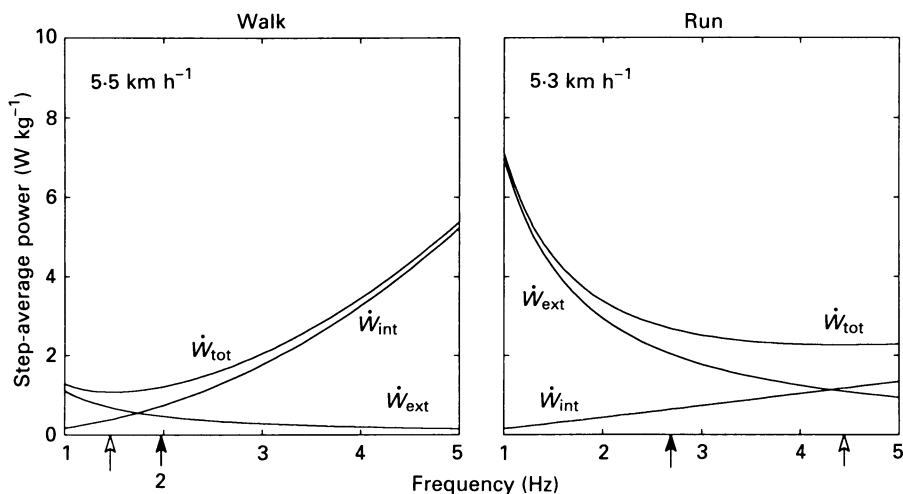


Fig. 6. The two graphs show, on the same scale and at about the same speed, how the mechanical power output is affected by the step frequency in running (same graph as Fig. 3) and in walking (same graph as Fig. 2B by Cavagna & Franzetti, 1986). Note that the frequency for a minimum of the total mechanical power (open arrow) is high in running, due to the high value of  $\dot{W}_{\text{ext}}$  at low frequencies, and low in walking, due to the high value of  $\dot{W}_{\text{int}}$  at high frequencies. Other indications as in Fig. 3.

mechanism of running. Consider Fig. 6, which shows, on the same scale and at the same speed (about 5.5 km h<sup>-1</sup>), how the mechanical power is affected by the step frequency in walking and in running. At an equal speed and step frequency,  $\dot{W}_{\text{ext}}$  is much smaller in walking than in running because the transfer between gravitational potential energy and kinetic energy of the centre of mass is large in walking (as in a pendulum) and about nil in running (as in a bouncing ball) (Cavagna *et al.* 1976); conversely,  $\dot{W}_{\text{int}}$  is larger in walking because the leg is more extended than in running and requires more work to be accelerated relative to the centre of gravity of the body (Marey & Demeny, 1885). It follows that at an equal speed of walking and running, i.e. at very low running speeds, the minimum of  $\dot{W}_{\text{tot}}$  will occur at a step frequency which is low in walking (due to the large value of  $\dot{W}_{\text{int}}$  at high frequencies) and high in running (due to the large value of  $\dot{W}_{\text{ext}}$  at low frequencies) (Fig. 6). The low  $f_0$  for walking at 5.5 km h<sup>-1</sup> corresponds to a rather large step length (1.04 m), whereas the high  $f_0$  for running at 5.3 km h<sup>-1</sup> corresponds to a small step length (0.33 m). When the step length is large the body is more exposed to the impact against the ground and an increase of the speed of locomotion will lead to a relatively larger increase of  $\dot{W}_{\text{ext}}$  which can be contained by increasing the step frequency. This explains why  $f_0$  increases from its low value with increasing speed of walking (Fig. 5). The reverse

is true for running: the large value of  $f_o$  at low running speeds makes  $\dot{W}_{\text{int}}$  (rather than  $\dot{W}_{\text{ext}}$ ) more susceptible to increasing with speed and this is accounted for by a decrease of  $f_o$  (Fig. 5).

*Oxygen consumption, mechanical power or force?*

Some studies show that the freely chosen step frequency in running is near to the most economical one as measured by oxygen uptake (Cavanagh & Williams, 1982; Kaneko *et al.* 1987). The optimum step frequencies determined by this criterion in the range of speeds from 12.6 to 16 km h<sup>-1</sup> fall within the standard deviation of  $f$  in Fig. 5, whereas at 9 km h<sup>-1</sup> the step frequency for a minimum of oxygen uptake (about 3 Hz: Fig. 2 of Kaneko *et al.* 1987) seems to be greater than the step frequency freely chosen by our subjects. As described above, the present study shows an agreement between frequency minimizing the step-average mechanical power (which should be related to the oxygen uptake) and freely chosen step frequency, only at intermediate running speeds. On the other hand, a minimum of the step-average mechanical power would correspond to a minimum of oxygen uptake only if the efficiency were constant. As discussed in a previous paper (Cavagna & Franzetti, 1986), the control of the step frequency on the basis of the energy output (metabolic or mechanical) would require learning or complicated perception mechanisms (Borg & Noble, 1974). Forces may be more easily sensed and kept to a minimum in the control of the step frequency. An example is offered by the respiratory apparatus: the respiratory frequency is more accurately predicted by a minimum of the average force exerted by the respiratory muscles (Meade, 1960) than by a minimum of mechanical power (Otis, Fenn & Rahn, 1950). In level terrestrial locomotion at a constant step-average speed, the muscular force performs an about equal amount of positive and negative work. Muscles are active and consume energy to maintain force both during positive work (when they shorten) and negative work (when they are stretched). The possibility that force development, instead of positive work production, is the origin of the energy expenditure in running has been proposed frequently in the literature (Taylor, Heglund, McMahon & Looney, 1980; Alexander & Ker, 1990; Kram & Taylor, 1990). The minimum of metabolic energy expenditure during running with the freely chosen step frequency (Cavanagh & Williams, 1982; Kaneko *et al.* 1987) may derive from a compromise which minimizes the step-average force exerted by the muscles to sustain the impact against the ground (particularly high at a lower step frequency) and the stiffening of the limbs (particularly high at a greater step frequency).

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